Joint
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Final Report

PART II
Design Subgrade Resilient Modulus

IMPLEMENTATION OF SUBGRADE RESILIENT MODULUS FOR PAVEMENT DESIGN AND EVALUATION

A. G. Altschaeffl
R. A. Duckworth
M. K. Clough

February 1998

Indiana
Department
of Transportation

Purdue
University

FINAL REPORT

"Implementation of Subgrade Resilient Modulus
for Pavement Design and Evaluation"

FHWA/INDOT/JTRP-98-2
Part II – "Design Subgrade Resilient Modulus"

by

A. G. Altschaeffl
Research Engineer

R. A. Duckworth
Laboratory Operations Consultant

and

M. K. Clough
Research Assistant

Purdue University
School of Civil Engineering
Joint Transportation Research Project
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Purdue University
West Lafayette, Indiana 47907
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16. Abstract

This Implementation Project had two purposes:

1) to update the INDOT Division of Materials and Tests' laboratory equipment and train personnel to properly conduct the testing for subgrade resilient modulus in accordance with new AASHTO testing protocol (AASHTO T-294-94);
2) to educate and train the geotechnical engineering section in the procedures for determining the design resilient modulus with minimum required testing, while using the database of the previous report on this subject, FHWA/IN/JHRP-92/23, "Subgrade Resilient Modulus for Pavement Design and Evaluation."

Part I of the Final Report, the detailed "Laboratory Procedures Manual," has been written for use by laboratory technicians having no formal engineering background. INDOT Materials and Tests Division personnel have been trained in performing the tests to the satisfaction of supervisory personnel.

Part II of the Final Report, "Design Subgrade Resilient Modulus," is the detailed summary of the procedures to be used in determining the design modulus for a project. In-service changes in water content and freeze-thaw effects are included. This report allows INDOT design engineering personnel to use laboratory test results and the previous database to determine properly the design resilient modulus for both new construction and in-service pavements.

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Final Report

"Implementation of Subgrade Resilient Modulus for Pavement Design and Evaluation"

To: Professor K. C. Sinha
Joint Transportation Research Project

February 1998

Project C-36-52Q

From: A. G. Altschaeffl

File 6-20-16

The Final Report on subject project is transmitted to you in 2 parts. Part I is a detailed "Laboratory Procedures Manual"; this has been written for use by laboratory technicians having no formal engineering background. INDOT Division of Materials and Tests personnel have been trained in following these procedures to the satisfaction of supervisory personnel.

Part II, "Design Subgrade Resilient Modulus", is the detailed summary of the procedures to be used in determining the design modulus for a project. This report allows INDOT design engineering personnel to use laboratory test results, and the data base from a previous project (FHWA/INDOT/JHRP-92-23) to determine properly the design resilient modulus for both new construction and in-service pavements.

This implementation project follows the previous SPR project whose report is referenced above. The testing protocol for resilient modulus has changed from the earlier project's AASHTO T-274-82 to the current AASHTO T-294-94. Because of this, and because INDOT wished to be able to test soils not explicitly in the previous project's data base, it was decided to create the current implementation project. Two components comprised this project: 1) update INDOT Division of Materials and Tests laboratory equipment, create necessary testing capabilities, and train technical personnel; 2) educate and train the geotechnical engineering section of the Materials and Tests Division, so to minimize testing to be required in determining the design resilient modulus for a project.

The contents of the two parts of this Final Report show that the objectives of the project have been fulfilled. Equipment updating was readily accomplished. Unfortunately, the original organization for software support unilaterally withdrew from the market. In-house operations managed to work around this major obstacle, albeit over a longer time frame. Laboratory personnel are now trained, ready for work. Design engineering personnel now can conform fully to the mandates of the AASHTO Guide for the Design of Pavement Structures with respect to the subgrade soils.

The contents of this report reflect totally the comments made by SAC reviewers. These comments improved this report and they are acknowledged and appreciated.

Respectfully submitted,

A. G. Altschaeffl
Research Engineer

INDIANA DEPARTMENT OF TRANSPORTATION
100 North Senate Avenue
Room 1101
Indianapolis Indiana 46204-2249
(317) 232-5533 Fax (317)-232-0238

REPLY TO:
Division of Materials and Tests
120 South Shortridge Road
Indianapolis, Indiana 46219
(317) 232-5280
FAX: (317) 356-9351

March 4, 1998

School of Civil Engineering
Geotechnical/Materials Area
Purdue University
1284 Civil Engineering Building
West Lafayette, Indiana 47907

Attention: Professor A. G. Altschaeffl

Re: "Implementation of Subgrade Resilient Modulus for Pavement Design and Evaluation" - Project C-36-52 Q

Prof. Altschaeffl:

Ross Duckworth has successfully completed the training phase of this project and is in the process of completing a draft of the procedure manual. Our Geotechnical Laboratory Supervisor and one Laboratory Technician have been trained and have demonstrated proficiency in conducting the procedures necessary to produce accurate results.

One variation in the original proposal for this work had to be accepted. The computer program will produce data only in non-metric form and that must be manually converted to metric units. This is not a crippling flaw, but it is a deviation from the original proposal. Through no fault of either the researchers or INDOT, we were unable to get the cooperation of either the equipment manufacturer (MTS Corporation) or the software designer Dr. G. Sousa in supporting the products they manufactured, since they had terminated their contractual relationship. The attempts at contacting Dr. Sousa resulted in two time extensions on this project. The result was that we were ignored and the decision was made that the project was important enough to warrant completion with this change.

Please contact us, if you require additional information. We look forward to reviewing the draft report.

R. K. Smutzer P.E.
Chief. Materials and Tests Division

rwr/RWR

cc: J. P. Bellinger
R. W. Rahn
N. Zia
File

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NOTE: This Implementation Report is a supplement to the project entitled, "SubgradeResilient Modulus for Pavement Design and Evaluation". The data herein are from Report FHWA/IN/JHRP-92-23; thus, Figure numbers, and captions are as in that report.

DESIGN SUBGRADE RESILIENT MODULUS

Implementation Report

The 1996 AASHTO Guide for the Design of Pavement Structures introduces the Resilient Modulus as a definite material parameter to characterize subgrade soil. The incorporation of resilient modulus into design practice requires development of testing capabilities and a procedure and data base to allow ready implementation. This study concentrated on development of a procedure to create the implementable resilient modulus for typical Indiana soils.

Five typical cohesive soils, ranging from an A-4 through A-6 to A-7-5 and A-7-6 classes were tested. It was found that laboratory compaction with impact procedures at standard Proctor energy at water contents near to optimum or slightly larger, depending on the soil, would create a soil fabric similar to that created in the field under current Indiana specifications. When this preparation is combined with the consideration created in this project for resilient modulus and the data from a "routine unconfined compression test", then the as-compacted modulus is obtainable somewhat readily for a specific location. This reduces the need for sophisticated dynamic testing equipment and its associated software.

In the field, in-service, the prepared subgrade experiences a variety of environmental conditions. Two seem especially important: freeze-thaw effects, and changes in water content. These have been included in the procedures developed in the project. The resilient modulus of the frozen – and thawed – soil states was developed through laboratory simulation. Additionally, a laboratory procedure was developed to add water, by injection, to the as-compacted soil. Relations were developed from results of testing to allow prediction of the change in modulus from the post-compaction change in water content, soil-by-soil.

From the foregoing results of this project, a procedure has been developed with which to determine the subgrade resilient modulus for use in pavement design. The procedure and associated charts and tables are presented below for new construction:

1) Identify the soil that will become the compacted subgrade. Procure a bulk sample for the laboratory (each specimen to be prepared requires about 1.4 kilograms of soil).

2) Prepare an impact compacted specimen in the laboratory, 71 millimeters in diameter and 142 millimeters in height in a suitable mold, according to the criteria in table 10.1 appropriate for the soil.

Table 10.1 Laboratory Compaction Criteria for Replication of Field Compacted Fabric

Site	Laboratory Compaction Method
South Bend (A-4/A-6)	Impact compaction at OMC to 1% wet of OMC with standard Proctor energy
Fort Wayne (A-6)	Impact compaction at OMC with standard Proctor energy
Washington (A-4)	Impact compaction at OMC with standard Proctor energy
Bedford (A-7-6)	Impact compaction at 1% wet of OMC with standard Proctor energy
Bloomington (A-7-5)	Impact compaction at 1.5 - 2% wet of OMC with standard Proctor energy

3) Perform an unconfined compression test, using the specimen from (2), at a strain rate of 1 percent per minute. Calculate the stress, in kPa, associated with 1 percent axial strain, $S_{u1.0\%}$.

4) Calculate the predicted <u>as-compacted</u> resilient modulus, in Mpa, from:

$$M_R = -11.03 + 0.832\,(S_{u1.0\%}) - 0.001\,(S_{u1.0\%})^2 \qquad \text{(equation 4.8)}$$

Note: $S_{u1.0\%}$ in units of (kPa), and M_R in units of (MPa).

5) Estimate the change in water content that is expected to occur in-service by using table 10.2. The sampling that was performed in this project, and the work of Prapaharan, Altschaeffl, and Dempsey (1985) with its additional referenced works suggest strongly the equilibrium water content, in service, will likely be near to that which represents 90% to 95% degree saturation for Indiana conditions. One must know what was the original compaction specification requirement for the average water content of the as-compacted soil.

Table 10.2 Resilient Modulus for Frozen Soils and Estimate of Water Contents after Construction

Sites	R_{rf} (MPa)	As-compacted optimum water content, (%)	Estimate of water content at $S_r = 90\%$	Estimate of water content at $S_r = 95\%$
South Bend, (A-4 / A-6)	186	9.8	10.8	11.4
Fort Wayne, (A-6)	186	16.8	17.2	18.2
Washington, (A-4)	317	15.0	16.4	17.4
Bedford, (A-7-6)	186	19.5	20.0	21.1
Bloomington, (A-7-5)	186	23.0	23.9	25.3

Today, Indiana's earthwork specification aims for the average water content to be near to 1/2% dry of optimum water content. Thus, the change to be expected is the difference between the as-compacted average and the water content at the likely in-service degree of saturation.

6) Estimate the change in M_R that is expected from the change in water content predicted in (5) above. Presented below are the diagrams to allow this prediction, soil by soil.

7) Estimate M_R at equilibrium and call it the normal subgrade condition:

$$M_{RN} = M_{R\ as\text{-}comp} - \Delta M_R$$

Note: All values in units of (MPa)

Where ΔM_R is that due to the expected change in water content, from (6) above.

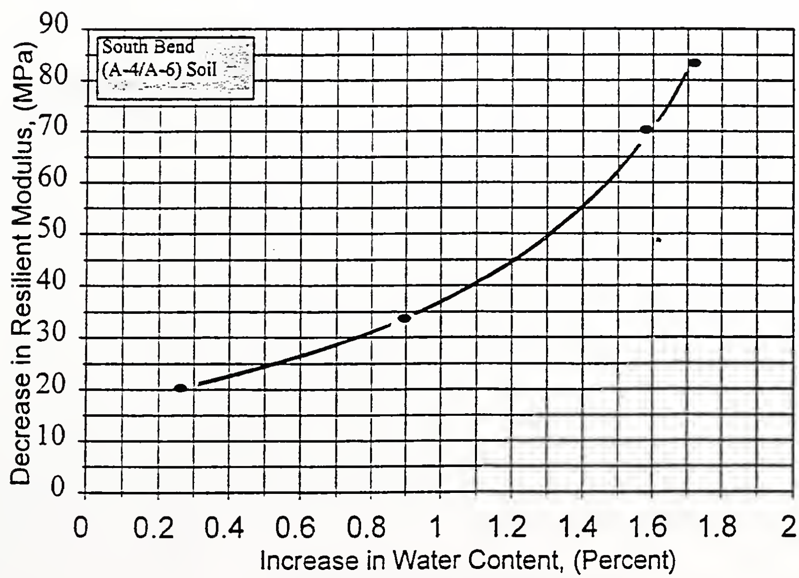

Figure 10.1 Relationship Between ΔM_R and Δw - South Bend (A-4 / A-6)

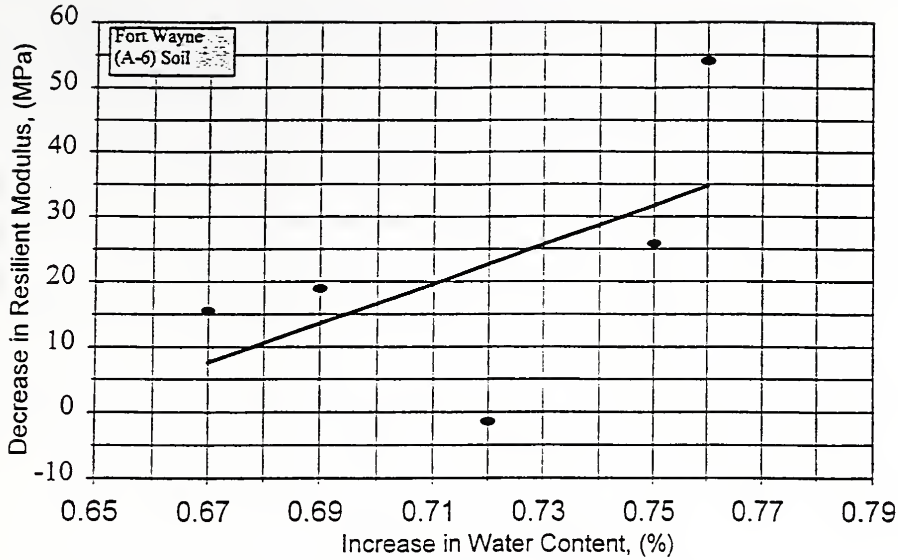

Figure 10.2 Relationship Between ΔM_R and Δw - Fort Wayne (A-6)

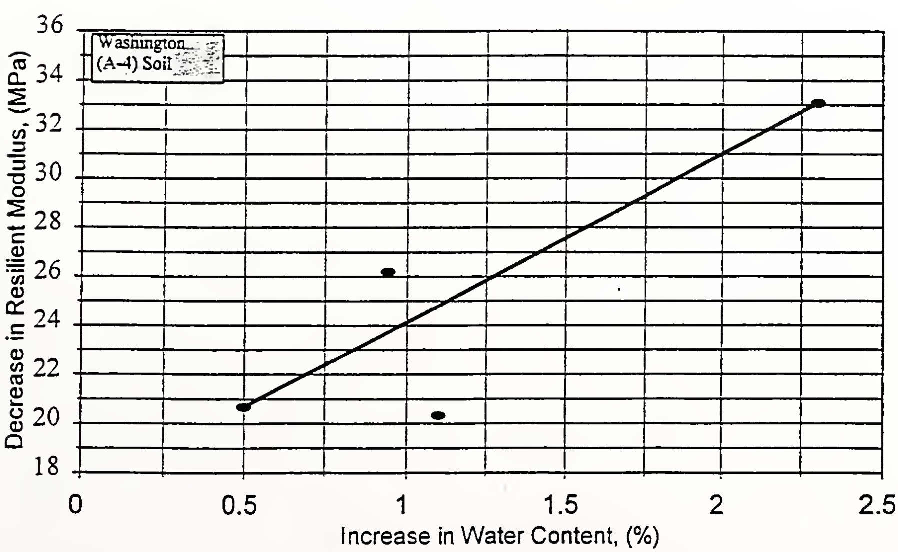

Figure 10.3 Relationship Between ΔM_R and Δw - Washington (A-4)

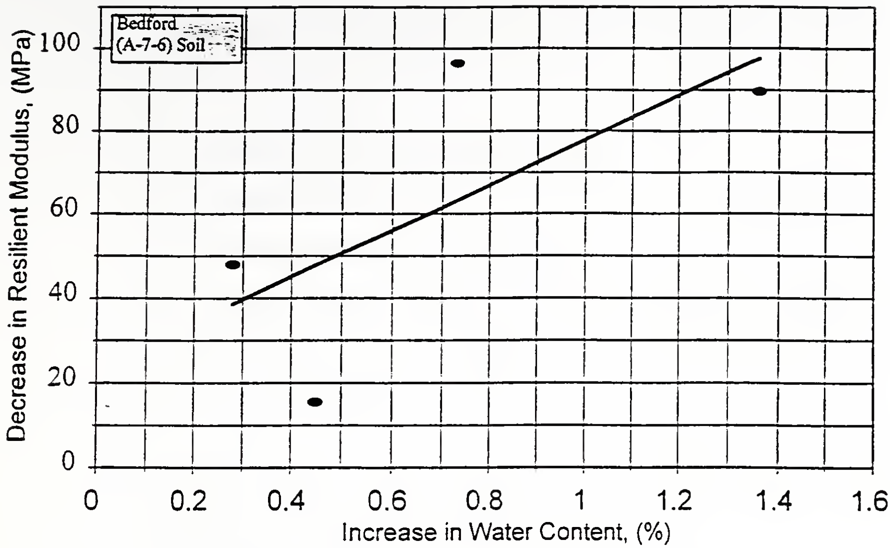

Figure 10.4 Relationship Between ΔM_R and Δw - Bedford (A-7(6))

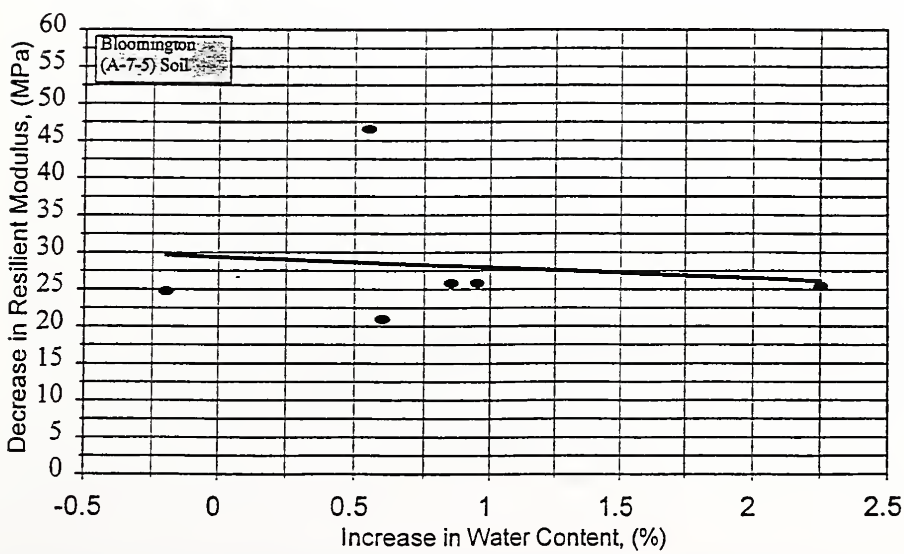

Figure 10.5 Relationship Between ΔM_R and Δw - Bloomington (A-7(5))

8) Estimate M_R for the frozen condition by using Table 10.2 for the appropriate soil.

9) Estimate M_R for the <u>thawed</u> condition by using:

$$M_{RT} = 16.91 + 0.1302\ (S_{u1.0\%}) \qquad \text{(Equation 5.3)}$$

<u>Note:</u> $S_{u1.0\%}$ units of kPa, M_{RT} units of MPa

Where $S_{u1.0\%}$ is the stress causing 1.0% strain in the unconfined compression test for the normal condition. The magnitude of $S_{u1.0\%}$ is back calculated from equation 4.8 using M_{RN} as above (item (7)).

10) Estimate M_R for each month by constructing a chart such as Figure 10.12. This requires a judgement on when the subgrade will be frozen, when thaw is complete, and when the "normal" condition is present.

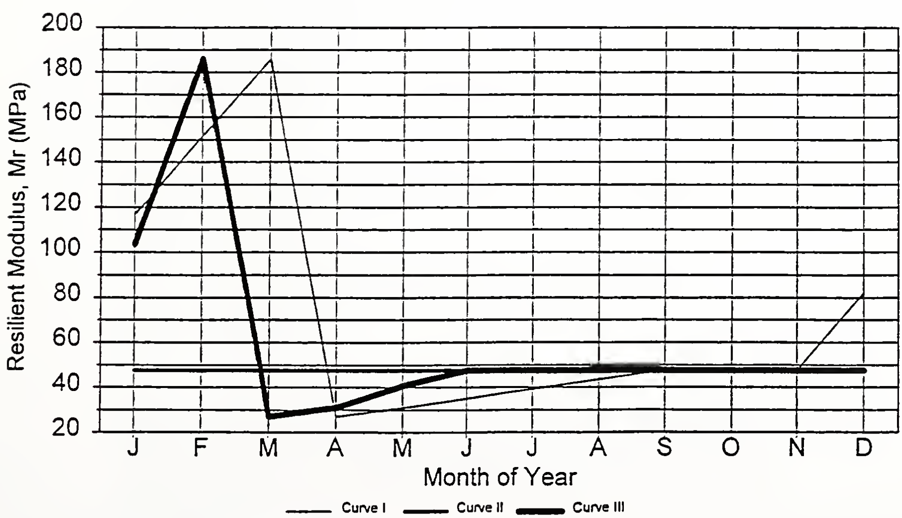

Figure 10.12 Seasonal Resilient Modulus Values for the Example (Report Section 10.10.1)

11) **An Example:**

Let us assume a site whose subgrade soil is as that at the South Bend site of this project, an A-4 / A-6 soil. Let us assume that an unconfined compression test was performed (item (3) above) on a specimen prepared as per item (2) of this procedure - and let us assume that the stress causing 1.0% strain is 137.90 kPa from the test results.

According to item (4) above, the as compacted resilient modulus is:

M_R = **-11.03 + 0.832 (137.90) - 0.001 (137.90)^2**

M_R = 84.7 MPa *Note:* $S_{u1.0\%}$ in units of (kPa), and M_R in units of (MPa).

Let us assume the estimate is made that water content will increase to create 90% degree of saturation, from an as-compacted at-optimum water content, i.e. $\Delta w = 1.0\%$ from table 10.2. From the South Bend site diagram (Figure 10.1) of item (6) above, **ΔM_R = 37.1 MPa** for the $\Delta w = 1.0\%$, therefore:

M_{RN} = 84.7 - 37.1

M_{RN} = 47.6 MPa *Note:* All values in units of (MPa)

The $S_{u1.0\%}$ that is associated with MR = 47.6 MPa is back calculated from equation 4.8. Thus:

47.6 MPa = -11.03 + 0.832 ($S_{u1.0\%}$) - 0.001 ($S_{u1.0\%}$)^2

$S_{u1.0\%}$ = 77.73 kPa

The magnitude of $S_{u1.0\%}$ associated with the normal condition M_{RN} is inserted into equation 5.3, to determine the thawed condition modulus, M_{RT}.

M_{RT} = 16.91 + 0.1302 (77.73) *Note:* $S_{u1.0\%}$ units of kPa, M_{RT} units of MPa

M_{RT} = 27.0 MPa

From Table 10.2, the frozen condition modulus, **M_{RF} = 186 MPa.**

11) **An Example (continued):**

In this example, the fully frozen condition is expected at the beginning of March, thaw is expected to be complete at the beginning of April, the normal condition is expected from the beginning of September to the beginning of November, at which time freezing starts. This set of judgements is shown as Curve I on Figure 10.12.

In order to determine the sensitivity of the design M_R (as per AASHTO Design Guide) to judgements about frozen, thawed, and normal conditions of subgrade, two additional sets of judgement examples were created. These are shown as Curves II and III on Figure 10.12.

The assembly of month-by-month moduli to create the design M_R is shown on Table A of this report. The monthly magnitudes of M_R are taken from the appropriate Curves of Figure 10.12, assuming a linear variation between the dates selected for the various subgrade conditions.

The data of Table A suggests that the design M_R may not be very sensitive to varying judgements about subgrade conditions.

The example presented was made using relations that are associated with an in-service confining pressure, σ_3, of 0.0207 MPa (20.7 KPa), and an applied loading deviator stress, σ_D, of 0.0414 MPa (41.4 KPa). The report provides a procedure to create the relations (used in the example) that correspond to other magnitudes of σ_3 and σ_D.

TABLE A. Calculation of Design Modulus. (Refer also to figure 10.12)

Curve I: Freezing begins November, thawing begins March, thawing ends April, normal equilibrium established September.

Curve II: No freezing / thawing; normal equilibrium the full year.

Curve III: Freezing begins December, thawing begins February, thawing ends March, normal equilibrium established June.

Month	M_R (MPa) Curve I	M_R (MPa) Curve II	M_R (MPa) Curve III	u_f Curve I	u_f Curve II	u_f Curve III
January	117	48	103	0.018	0.147	0.024
February	151	48	186	0.010	0.147	0.006
March	186	48	27	0.006	0.147	0.550
April	27	48	31	0.550	0.147	0.395
May	31	48	41	0.395	0.147	0.211
June	35	48	48	0.295	0.147	0.147
July	39	48	48	0.228	0.147	0.147
August	43	48	48	0.181	0.147	0.147
September	48	48	48	0.147	0.147	0.147
October	48	48	48	0.147	0.147	0.147
November	48	48	48	0.147	0.147	0.147
December	82	48	48	0.041	0.147	0.147
			Sum =	2.165	1.764	2.215
			u_f avg. =	0.180	0.147	0.185
			M_R (MPa) =	43	47	43

$u_f = 1.18 \times 10^8 * (M_R \div 6.8947 \times 10^{-3})^{-2.32}$ $u_f \text{ avg} = \sum (u_f \div 12)$ Design $M_R = 20.786 * (1 \div u_f \text{ avg})^{(1-2.32)}$

Note: u_f and u_f avg. Converted to psi to allow use of AASHTO Pavement Design Guide equations.

The example reported was made for a __new-construction__ situation. If the situation is of a **__reconstruction__**, i.e., using a subgrade that has been in-service, then the following changes are made to the described procedure.

1) The subgrade is sampled by pushing a 76.2 mm diameter Shelby tube to create the specimen for unconfined compression testing.
2) Using $S_{u1.0\%}$ obtained from the unconfined compression test, enter equation 4.8 to determine M_R. Because the subgrade has been in-service, its water content should be at the "normal" condition; The calculated M_R, then, is M_{RN}, as in the example.
3) The remainder of the procedure is as before, in the example.

Granular dense sand was also studied in this project. The resilient modulus was found to be independent of water content, and dependent on dry density and the stresses confining the specimen. The following relation may be used to predict the modulus:

$$\mathbf{M_R = (-44.0714 + 0.509\ RC)\ \theta^{0.595}}$$

Where M_R = resilient modulus, MPa

Where θ = sum of the principal stresses, kPa

Where RC = relative compaction in percent = ratio of the as-compacted dry density to that obtained from 5-layer compaction by 5-minute vibratory compaction per layer on a shake table operating at 50 Hz.

The report contains a procedure by which the compaction specification can be developed that will assure the presence in the subgrade of a limiting desired specific resilient modulus. This procedure requires some agreement on what should be the limiting allowable deflection of a pavement surface, an agreement not now available.

During a meeting between InDot personnel on July 12, 1996 the pavement design program (DARWin(tm)) was utilized to determine pavement thickness sensitivity to different magnitudes of resilient modulus. The results of the simulations showed that with all other parameters being equal, variations of resilient modulus of 1 MPa or less were not significant with respect to pavement design thickness. It is therefore recommended that the design value for resilient modulus, obtained using the procedure outlined in this manual, be rounded off to the nearest whole number.

During this meeting, InDot reported that the following minimum and maximum pavement thickness values were currently used:

1) Flexible Pavement:
   a) 12 inches minimum
   b) approximately 21 inches maximum
2) Concrete Pavement:
   a) 10 inches minimum
   b) approximately 15 inches maximum

It can be assumed that design resilient modulus values, under some circumstances when used in conjunction with the (DARWin(tm)) design program, would indicate a pavement thickness which does not comply with the current InDot pavement design thickness guidelines. When such a case arises it is the responsibility of the engineer to ensure that the minimum and maximum pavement thickness, as defined by the current InDot design criteria, are not violated.